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Development and Evaluation of Sensor Concepts for Ageless Aerospace Vehicles

Threats and Measurands

David Abbott, Shaun Cunningham, Graham Daniels, Briony Doyle, John Dunlop, Dean Economou, Tony Farmer, David Farrant, Cathy Foley, Bruce Fox, Mark Hedley, Jan Herrmann, Colin Jacka, Geoff James, Mark Johnson, Barry Martin, Geoff Poulton, Don Price, Torsten Reda, Grahame Rosolen, Andrew Scott, Philip Valencia, Damon Ward, John Winter, and Alan Young

Commonwealth Scientific Industrial Research Organisation
Telecommunications and Industrial Physics
Lindfield, New South Wales, Australia

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1. Introduction

1.1 Project Aims

NASA's goal of ageless aerospace vehicles requires the development of vehicles that are capable of structural self-assessment and repair. These functions can be divided between those carried out by distributed sensors and intelligent processing and communication on the skin or within the structure, and those that could be more effectively provided by autonomous robotic NDE agents which could be deployed to monitor damage or integrity of the vehicle structure.

Critical to the success of the Ageless Vehicle program are the development of appropriate technologies for non-destructive evaluation of structures, and the development of strategies and technologies for processing NDE data, storage and communication of NDE information, and analysis of NDE data with capability for intelligent decision-making.

The aim of this project is to develop and critically examine concepts for integrated smart sensing and communication systems that could form the distributed sensing function of a smart vehicle. Such an integrated system may include components deployed for structural monitoring on an NDE agent.

1.2 Purpose, Scope and Outline of This Report

The purpose of this report is to present a list of the types of threats to which an aerospace vehicle is subject, and which it must be capable of surviving if it is to be considered ageless. General strategies for detecting either the approaching realization of these threats, and/or their effects are also listed, as are the quantities that must be measured for implementation of the strategies. Required measurement rates and response times for the various threats are also considered, and the implications of this for the type of sensor and the nature of the response are discussed. Thus, this report sets the scene for the main work of the project: it establishes in broad terms the requirements that must be satisfied by the integrated sensing system.

There are two reasons for the preparation of this report at this stage of the project, approximately two months into a six-month work period. The first is to initiate a dialogue with personnel from the NASA Nondestructive Evaluation Sciences Branch (NESB) aimed at ensuring that the significant performance requirements of a sensing system have been captured, and that the proposed future directions of the work are consistent with NESB expectations. We welcome comments from NESB personnel concerning any aspects of this report.

The second reason was to ensure all members of the CTIP team, which is drawn from a variety of disciplines and backgrounds, had an opportunity to think about, discuss and contribute to the development of the system requirements. Most team members have contributed in depth to the discussions that have led to this report, and consequently have developed a sound appreciation of many of the important issues involved.

While it is expected that in the longer term CTIP will contribute significantly to the development of appropriate sensors for ageless systems and of measurement principles and techniques for solving outstanding relevant NDE issues, the main thrust of the present project is to develop concepts for the whole integrated system: for sensing, data processing, storage, communication and decision-making. Therefore, it has been assumed that it is not necessary at this stage to work within a scenario that contains all conceivable threats for all classes of future operational conditions, as long as it contains a sample of possible threats that is representative in terms of the type and severity of potential damage, the time taken for damage to occur or accumulate, opportunities for prior detection and avoidance, the nature and timescale of appropriate responses, etc. In short, the scenario must be representative in terms of requirements on the functionality of the system.

This report is limited in scope to a listing of the threats, both from the external environment and from within the vehicle and its structure, and strategies for detecting damage that may result from these threats. It does not discuss measurement techniques or technologies in any depth, even though some of the more interesting discussions within the team have revolved around measurement techniques. This is partly because sensing and measurement techniques will be influenced to some extent by communications and decision-making requirements, and partly because the choice and availability of sensing technologies will change with time. These issues will be dealt with later in the project.

The structure of this report is as follows. A number of issues have been raised during the course of our discussions. Some of these are pertinent to the list of threats, and will discussed in the next section, followed by the threats and sensing strategies. Following this a list of required measurement rates and response times is presented. The other issues mentioned above are then addressed. These are mostly not resolved, but are raised as issues for discussion and resolution at a later time. Finally, there is a brief outline of how we plan to proceed with this project in the immediate future.

2. Preliminary Issues

Issues which impinge directly on the identification of threats and sensing requirements for an ageless vehicle are:

- the nature of threats to be considered;
- the nature and purpose of the vehicle;
- vehicle structure and the capabilities of materials.

2.1 The Nature of the Threats to be Considered

A threat is considered to be any event, situation or characteristic that can result in damage to the vehicle or can produce an impairment of its function. Threats will be referred to as external if they result directly from the external environment in which the vehicle is operating (e.g. weather conditions in the atmosphere, cosmic radiation), or internal if they are generated within the vehicle, or indirectly due to the external environment (e.g. material fatigue, pressure leaks, electronic system failure).

It was decided that malicious threats would not be considered explicitly, partly because of the enormous variety of ways in which malicious damage could be inflicted on a vehicle, and by means in the future that we probably cannot imagine now. However, the effects of many forms of malicious damage will be similar to those of accidental or unavoidable damage.

The possibility was considered that we should concentrate on threats that lead to “ageing” of a vehicle, i.e. those that produce relatively slow progressive degradation of the materials and structure. Certainly this damage is among the most difficult to detect at an early stage (at least by current methods in existing materials) and needs to be a central part of the strategy, but the ultimate objective is to develop a sensing system for a vehicle that must have long-term survivability. This means it must be able to recover from the whole range of fast and slow damage processes (and be capable of avoiding potentially catastrophic incidents).

2.2 The Nature and Purpose of the Vehicle

There are three significantly different environments in which future aerospace vehicles are likely to be required to operate. These may be summarized as follows.

A. A space vehicle, which would operate only in space, and never in the earth’s atmosphere. It would dock, and could be serviced if necessary, at a space station. It would not be subject to the rigours of atmospheric travel (turbulence, drag, heat generation, etc.) but flights would be long, leading to a strong requirement for structural reliability and longevity. Such a vehicle may still need to be capable of negotiating an atmosphere, and perhaps one of undetermined pressure and composition, e.g. at a destination planet. External threats (radiation, particles, micro-meteoroids etc.) may be significant.
B. A “shuttle”-type vehicle, which commutes between earth and space (e.g. to a space station, the moon, …). It must be capable of handling high-speed atmospheric travel, and large accelerations, including the heat of re-entry. Flights

will probably be shorter than for the space vehicle. Human intervention in the maintenance process, if required, could be available on earth or at a space station.

C. An atmospheric vehicle (aircraft), which may have performance requirements comparable to those of present aircraft. Requirements could range from short low-level trips (inter- and/or intra-city) to longer haul (inter-continental) flights. It can probably be assumed that the latter would be fast and high, leading to similar requirements to the shuttle vehicle (B).

In general it is only the threats posed by the external environment that are different for the different vehicle types. However, the severity, frequency and relative importance of internal threats may be different, as are the opportunities for and means of repair. These will make clearly important differences in practice. Threats to all of these types of vehicles have been considered.

2.3 Vehicle Structure and Capabilities of Materials

The group held a long and interesting speculative discussion about the nature of vehicles and the sorts of materials and structural principles from which they might be constructed at some time in our distant imaginations. While this discussion did not result in a consensus being reached (which in retrospect was both inevitable and desirable), it stimulated long-term thinking, and a number of useful points emerged.

Two specific models of materials and structures were considered, based on proposals presented by two group members, Torsten Reda and Mark Johnson. One was an explicitly biological model, based on continuous regeneration of cells of the structure from generic material that is capable of assuming the required characteristics of any part of the structure according to the information contained in the cell's nucleus (DNA-like) and the chemical environment in which the cell finds itself. The other was a more engineering-oriented model, but of a similarly self-regenerating structure. In this case the structure was composed of identically-shaped modules, capable of self-assembly into a variety of structural shapes, and with each one carrying out a specific function related to the sensing and repair of damage.

These models led to considerations of the requirements of a sensing system that are (relatively) independent of the capabilities and properties of the materials.

Whether or not the ultimate aerospace vehicle is, in whole or in part, a self-assembling, self-regenerating structure, it is highly likely that it will contain materials that have some capability for self-healing. Such materials are already under development: composites that contain micro-globules of resin and hardener dispersed within their microstructure have been reported, even though in this case the self-repair mechanism is relatively unsophisticated and non-repeatable. We need to consider the implications of this for a sensing, communication and supervisory system.

Self-repair of a material or structure requires that, at some level, the material or structure must "know" it has been damaged. The following are possible scenarios for damage detection and repair.

1. The damage could be repaired as part of a continuous regeneration process. This might be appropriate for slowly accumulating damage, such as may occur due to fatigue, wear, corrosion or radiation. In this case the regeneration cannot be simple replacement: it must be based on information about the undamaged material.
2. The damage is detected and repaired "automatically" by the material or its local environment (i.e. without reference to other parts of the structure), not by a continuous process but "on demand" in response to the detection of damage. If this is to be carried out repeatedly, as required, then both information (possibly stored locally) and a supply of replacement material on demand are required.
3. The damage is detected, locally or remotely, and the repair process is initiated (and possibly controlled) by another part of the structure.

These three scenarios require rather different balances to be struck between sensed information that is used locally to initiate and control repair/healing/regeneration, and that which is communicated to other regions of the structure.

While scenario 1 may not actually require the active detection of the particular forms of slowly accumulating damage, such "automatic" repair would imply that the system continuously regenerates at a rate that does not depend on the rate of damage accumulation, yet it regenerates sufficiently quickly that damage is repaired before it can accumulate beyond some critical level. The efficiency of such continuous regeneration would need to be examined: while materials may be recyclable, the process would consume energy. In any case, it is likely that a supervisory system would want to know if this sort of damage was occurring, and its rate of progression.

Scenario 2, which allows for local repair/regeneration, but "on demand" in response to the detection of damage, requires some form of communication to another part of the structure, at least for the supply of replacement material.

It therefore seems likely that, whatever the capabilities of the materials for self-repair or regeneration, there will be a requirement for knowledge of the occurrence and nature of damage to be communicated to some region or regions of the structure remote from the damage site.

Another significant issue relating to material capabilities is that of information. Any self-repairing or regenerating material requires information, energy and a source of new material (nourishment).

- For biological systems, the information is stored locally in the cell nuclei. Thus each cell of the system contains a huge amount of information, much of which may not be relevant at that specific location. The provision of nourishment for regeneration, and the removal of waste products, are carried out differently according to the type and complexity of the system. The central supervisory system (central nervous system, brain) in higher animals may play a role in damage repair (and certainly in implementing strategies for damage minimization), but in simpler systems the information required for repair and regeneration appears to be maintained entirely locally.

- For the current generation of self-healing composites, the “information” content and the ability to repair the material are both very limited. Only one phase of the composite (the epoxy matrix) can be repaired, and the required information is, presumably, contained in the distribution and content of the adhesive globules, and thus is entirely local.
- In general, one would imagine that the information required to repair a material or structure would be most efficiently maintained in some combination of local and distributed (or centralised) storage.

As a final (self-evident) comment, it is worth noting that biological models of self-repair are somewhat imperfect:

- There is a very obvious process of ageing, ultimately due to a loss or corruption of local information for regeneration.
- Even in the absence of ageing, over-use injuries (in some cases analogous to fatigue in engineering materials), stress fractures, wear (e.g. at joints), etc. occur that are not adequately repaired without external intervention.
- Biological systems are successful statistically rather than individually. The aim here is to design vehicles with as close to 100% survivability as possible.
- Reliance on local information storage may introduce a new threat – errors leading to self-destructive behaviour, such as cancer in biological systems. On the other hand, the existence of a central brain and nervous system in higher animals represents a region of high vulnerability of the system.

Thus, biological models can provide very useful and interesting ideas for ageless vehicles, but their limitations must be recognized.

3. Threats and Measurements

This section contains a list of the threats that have been identified, and of the quantities that need to be measured to detect (or avoid) damage resulting from the threats. Following this, the requirements for measurement rates and response times are listed.

3.1 Classification of threats

There are various ways of classifying threats, such as:

- nature of threat;
- origin of threat: external vs internal;
- seriousness: catastrophic vs non-catastrophic;
- rate of damage progression;
- nature of damage: mechanical, electrical, thermal, chemical, … ;
- affected region of vehicle: skin vs viscera.

Classification here will be according to the nature of the threat. However this, like any classification, has obvious ambiguities and duplications.

3.2 Threats, effects and sensing strategies

- ***Impacts***
  - ***Large body and/or high velocity***

    Characterised by ability to create severe local or general damage, possibly catastrophic. Caused by external influences. Avoidance must be the prime defence, utilising radar, altimeter, optical detection – detect and predict trajectories.
    - Meteoroids, asteroids, substantial bodies in space.
    - Ground.
    - Collisions with other vehicles.
    - Large or fast debris (space junk, etc.).

    Effects: Large momentum change at impact, significant structural and material damage, shape change.

  - ***Small body or relatively low velocity***

    Characterised by ability to create (severe?) local damage, but not generally catastrophic. Generally caused by external influences.
    - Micro-meteoroids.
    - Bird strike.
    - Debris (space junk, tyre debris, runway debris, …).
    - Dropped tools.

    Effects: Vibration, strain, elastic wave generation, structural or material damage, possible shape change, possible loss of material.

  - ***Small particles***

    Individual particles cause minimal (if any) damage, but large numbers can cause distributed damage to structure.

- Hail.
- Small particles, dust.

Effects: Multiple distributed impacts (vibration, strain, elastic wave generation), surface damage.

Sensing strategies for impacts:

- – Detect prior to impact (radar etc.) and avoid if possible.
- – Detect impacts at time of occurrence (surface detection, elastic wave), detect momentum transfer, mass or shape changes.
- – Sense and characterise damage following impacts (see below under material failure, material degradation).

❑ ***Radiation (external sources)***

- Ionising (cosmic, gamma, X-rays, beta, ionised particles, neutrons, UV, …).
- Optical.
- Thermal.
- Electromagnetic (em interference).

Effects: Radiation damage to materials, electronic systems, information store, etc., health effects of radiation, em interference with electronic control, navigation, sensing systems, effects of thermal radiation covered below.
Sensing strategies:

- – Detect radiation. Spatial flux variations small – few sensors required. Temporal flux variations dependent on vehicle speed. Assume small.
- – Detect damage. Radiation damage to materials detected as for other forms of material degradation (below). Electronic system tests and diagnostics.

❑ ***Radiation (internal sources)***

- Ionising radiation (reactors, fire/smoke detectors, medical sources, …).
- Electromagnetic (electronic systems, communications, …).
- Thermal (covered separately below).

Effects: As for external radiation sources
Sensing strategies:

- – Detect radiation. Position appropriate sensors near known sources.
- – Detect damage/interference. As for external radiation.

❑ ***Atmosphere***

- Friction (heat generation, drag).
- Weather (turbulence, vortices, wind shear, lightning, …).
- Temperature.
- Chemical composition.
- Dust, ash.

Effects: Outer surface effects of friction and temperature – extreme heat producing material failure or degradation, ice may impede control surfaces. Extreme weather may affect flying ability (possibly catastrophically), or may produce material failure

or degradation (fatigue). Chemical composition of atmosphere may cause surface damage (corrosion) or may constitute a health hazard. Dust, ash can cause blockage of air inlets (e.g. engines) for aircraft, which could be catastrophic.
Sensing strategies:

- Detect extreme weather conditions in advance (radar, lidar, acoustic) and avoid. Similarly for dust, ash.
- Temperature measurement at surface, including spatial and temporal rates of change.
- External (selective) chemical sensor.
- Detect material failure, degradation as below.

❑ ***Material failure (mechanical)***

- Fracture, cracking.
- Debonding.
- Delamination.
- Joint failure.
- Melting.

May be produced by impacts, the end result of material degradation (see below), external forces, e.g. due to extreme weather conditions, flying outside the specified envelope, etc.
Effects: Structural failure (possibly catastrophic), reduced structural strength, increased load transferred to other structural components, possibly causing progressive failure, reduced resistance to heat.
Sensing strategies:

- Detect occurrence of failure – displacement (strain), vibration, elastic wave.
- Detect damage – lack of material continuity, change of shape, altered stress/strain response.

❑ ***Material degradation (surface)***

- Wear (friction).
- Erosion.
- Corrosion.

Degradation induced by interaction at a surface of the material (free surface or interface with another material).
Effects: Microstructural modification, loss or gain of material, local heating, chemical modification.
Sensing strategies:

- Detect agent or detect products (particles from wear, erosion, chemical products from corrosion).
- Detect surface modification (shape, roughness, chemical potential, …).
- Detect loss of material, loss of desired properties (strength, conductivity, …).

- ***Material degradation (bulk)***
    - Fatigue (mechanical, thermal).
    - Creep.
    - Depolymerisation.
    - Degraded interface adhesion.
    - Dealloying.
    - Biological breakdown.

  Degradation within bulk material caused by stress (or cyclical stress), temperature (or temperature fluctuations), radiation, etc. Accumulates with time, generally beginning as insignificant microstructural damage distributed through a region of material, but has the potential to lead to catastrophic failure.

  Effects: Microstructural defects, leading to loss of strength, elasticity, electrical properties, optical properties, etc., cracking and (ultimately) failure.

  Sensing strategies:
    - Early detection of microstructural damage highly desirable.
    - Detect degradation of required material property (elastic, electrical, optical, etc.).

- ***Leaks***
    - Fuselage/outer skin, seals.
    - Fuel tanks, fuel lines.
    - Hydraulic lines.
    - Lubricants.
    - Water.
    - Process chemicals (gases, liquids).
    - Coolants.

  Leaks may occur across high or low pressure gradients, they may be fast or slow, they may be innocuous or catastrophic. Required responses and response times therefore vary widely. Generally caused by material failure, or joint failure.

  Effects: Loss of material (gas, liquid), loss of pressure, flow increase, contamination, corrosion.

  Sensing strategies:
    - Detect changes of pressure, flow, material (i.e. indirect detection).
    - Detect presence of leaking material, contamination, sound of leak (i.e direct detection of leak).
    - Detect material or joint failure.

- ***Contamination***
    - Air.
    - Fuel.
    - Water.
    - Lubricants, hydraulics, coolants.
    - Process chemicals.

May be caused by leakage, wear (e.g. contamination of lubricants) or failure of a process (e.g. water, air purification, waste disposal). Contaminants can be inert or active, can be expected or unexpected, and can represent a wide range of danger levels.
Effects: Degrades (more or less completely) functions of material that has been contaminated, may induce corrosion.
Sensing strategies:
- Detect presence of contaminant.
- Detect contamination mechanism (leakage, wear, …).
- Detect degraded function of contaminated material.

- ***Electrical/electronic failure***
  - Power source.
  - Wiring (power and signal reticulation).
  - Computers.

  A large area of concern, much of which is now covered by self-diagnostic systems and system redundancy. Ageing wiring is a major outstanding concern in current vehicles. Electrical noise might indicate malfunction.
  Effects: Minor or major system failure, shorts, sparks, fire, explosion.
  Sensing strategies:
  - Detect system malfunction (functional self-test).
  - Detect material degradation (preferable) or failure.
  - Detect indirect symptoms of failure (electrical noise, heat, sparks, fire, …).

- ***Engine malfunction/failure***
  Dependent on engine type, of course.
  - Wear.
  - Mechanical failure.
  - Fuel leakage, blockage, contamination.
  - Control system failure
  - Coolant system failure.

  Effects: Loss of power, engine failure (potentially catastrophic), fire.
  Sensing strategies: Covered elsewhere.

- ***Control systems***
  System failures, whether systems are electronic, hydraulic, optical, inertial, …
  - Navigation system.
  - Drive system.
  - Communications system.
  - Sensing system.
  - Life support system.
  - Waste disposal system

  Effects: Various levels of system malfunctions, to total system failure. Threats range from minor to catastrophic.

Sensing strategies:

- Detect system malfunction (functional self-test), perhaps using redundant system components.
- Detect cause of failure – material degradation or failure, leak, contamination, electrical malfunction/failure, etc.
- Detect indirect symptoms of failure.

❑ ***Fire***

Many possible causes, always dangerous, sometimes catastrophic.
Sensing strategies:

- Detect preconditions: heat, leakage/contamination of flammable materials.
- Detect smoke, other gaseous products, heat.

❑ ***Explosion***

Always dangerous, potentially catastrophic. Important to detect preconditions and prevent.
Sensing strategies:

- Detect preconditions: heat, leakage, contamination.
- Detect occurrence: pressure wave in gas (shock) or solid structure, vibrations, fire, structural damage.

❑ ***Thermal***

- External conditions (cold in space, re-entry heat, icing, …).
- Heat generated by mechanical systems (friction).
- Heat generated by electrical/electronic systems.
- Heat generated by chemical systems.
- Heat generated by fire, explosion.
- Temperature gradients, temperature fluctuations.

Effects: Material degradation (over or under temperature, or thermally induced fatigue), material failure, degradation or failure of various systems (electronic, etc.), threat to life, threat to storage of biological or other perishable or temperature-sensitive materials.
Sensing strategies:

- Measure temperature at appropriate locations.

❑ ***Sound and vibration***

- Passenger comfort – cabin noise.
- Pressure/shock waves.
- Material degradation (wear, fatigue) induced by vibration.
- External noise (aircraft).

Sources of noise and vibration may include engines, mechanical systems within the vehicle, air flow over the outer surface, noise generated by people. Noise may be used to assess operating condition of machinery (condition monitoring), and in some cases the formation of cracks or other forms of material degradation or failure (acoustic emission).

Effects: Indication of malfunction, material degradation, discomfort
Sensing strategies:

- Measure sound and vibration levels.
- Detect material degradation and/or failure as above.

- ❑ ***Other mechanical threats***
  - Acceleration (linear or angular) due to flight characteristics or atmospheric effects.

Effects: Structural stresses, damage from motion of movable objects, threat to passenger safety.
Sensing strategies:

- Detect preconditions (atmospheric, collision avoidance) and minimise effects.
- Detect with inertial system.

- ❑ ***Loss of information***
  - Control, navigation, sensing, repair systems.

Caused by radiation, noise, second law of thermodynamics.
Effects: Reduced ability to fulfil mission, reduced ability to faithfully repair, possibility to be ultimately catastrophic.
Sensing strategies:

- Redundancy.

- ❑ ***Software errors***

How intelligent can an “intelligent system” be? How “error-free” can be whatever form of code is generated to control it? How can such errors be detected?
Also related to loss of information.
Sensing strategies:

- System self-check and self-test.
- Redundancy.

- ❑ ***Human error***

Effects: Almost limitless.
Sensing strategies:

- Intelligent supervisory system and human-machine interface.
- Multiple levels of communication.
- See work (CSIRO and other) on risk assessment and mitigation in automated environments (e.g. factories, chemical engineering plants).

<u>3.3 Requirements for measurement rates and responses</u>

A. Quantities that may require a rapid response (< 1 sec).

1. ***Detect by remote sensing, external to vehicle***

   Detect in advance and calculate trajectory to enable avoidance.
   - Large/fast objects (substantial space objects (meteoroids etc.), other vehicles, space junk, earth, …).
   - Birds, dust, ash, particles, hail.
   - Turbulence.

   Use radar, optics, lidar, acoustic sensing as appropriate.

2. ***Detect on outer skin***
   - Radiation (ionizing, thermal, optical, …).
   - Temperature (friction).
   - Chemical composition.
   - Ice, etc. on skin.

   Use appropriate sensors on skin surface.

3. ***Detection of potentially catastrophic events as they occur***

   Initial detection of occurrence only. Use detection to initiate whatever immediate corrective action is possible (generally not repair). Assess damage and initiate repair (if possible) later.
   - Impacts: surface strain, sound, elastic wave, material discontinuity.
   - Fracture: sound, elastic wave, material discontinuity.
   - Leaks: flow, sound, direct chemical detection, crack or fracture?
   - Heat: temperature.
   - Fire: temperature, smoke.
   - Explosion: shock (pressure) wave, heat, smoke/other gas, damage (material discontinuity?).
   - Electronic or system failure (not including above causes): system malfunction or test response.
   - Engine malfunction (not including above causes): fuel contamination, fuel blockage.

B. Quantities that generally require slower response (1 sec to ~ 5 mins).

- Detect damage resulting from potentially catastrophic events (as listed in 3 above): shape change, material loss, material continuity, fluid/fuel loss, contamination from leaks, smoke or other gaseous contamination, … .
- Impacts by small bodies, small particles: detect impacts.
- Slow or less dangerous leaks: detect as in 3 above.
- Contamination: direct chemical detection.
- Corrosion (if associated with leak of corrosive material).

- Radiation from internal sources (some cases, e.g. leakage of radioactive material from a reactor, might require more rapid response): radiation detectors, chemical detection.
- Determine causes of system failure and detect/assess resulting damage.
- Thermal (temperature).
- Noise and vibration.
- Integrity of vehicle protective coatings – heat, radiation shields: detect “hot” spots.

C. Quantities that require only low measurement rate/response (mins, hours, …).

- Material degradation (surface and bulk).
- Detect damage from small body, small particle impacts.
- Radiation (external sources) – as long as rate of change, vehicle speed not too great: radiation detectors.
- Information integrity.

4. Further Issues for Discussion

4.1 Some Sensor Requirements and Measurement Issues
The lists in the previous section give an indication of the complexity of the requirements for the sensing and response system: measurements of a large variety of mechanical, chemical and electrical quantities, at a wide range of temporal and spatial scales. There is clearly a need to simplify and modularise the sensing and repair system as far as possible. This will require simplified (standardised, modularised) construction principles. Some thought has been given to this aspect of the problem, and it will be considered further over the next few months.

A number of quantities that have to be detected rapidly were identified above. These are associated with threats that could lead to catastrophic results for the vehicle. These quantities should be detected by sensors that are continually in position and continuously in operation. These sensors need to be either:

a) Integral to the material or embedded in the structure, obtaining local data, or
b) Remote but fixed, obtaining global information.

An example of the former might be an embedded strain sensor (strain gauge), while the latter could be an optical imaging system measuring surface shape. It may be advantageous for the embedded, continuously monitoring sensors to be passive. Physically movable or mechanically scanning sensors would probably not be suitable for rapid response monitoring. Electronically scanned sensors may be satisfactory in some circumstances, but maybe not in all.

The immediate response to indications of damage that could be classified as potentially catastrophic is unlikely to be repair. It is more likely to be some action that will reduce the severity of the consequences of the damage: examples are shutting down an engine, sealing off a compartment, changing flight characteristics, or a range of other responses. Assessment of damage and repair would generally be carried out later.

Measurements that do not require rapid response (e.g. detection of material degradation, or ageing, or detection of sub-critical damage) could employ movable sensors, perhaps mounted on autonomous agents. These might employ active measurements, which involve measuring the response to an applied stimulus such as a mechanical wave or an electromagnetic pulse. Autonomous agents could work cooperatively with the passive embedded sensors to carry out active measurements. This would require the autonomous agents to be strongly integrated into the vehicle sensing system.

An interesting analogy was made between a vehicle and a factory, in which processes are monitored for possible failure, and maintenance strategies are developed to ensure the overall efficiency of production. Research related to such scheduling and maintenance issues may well be relevant in the present case. This analogy also highlights the desirability of monitoring changes to processes or conditions. For example, if panels are considered, one can imagine measuring alignment and pressure, correlating data from different regions, individual panels making comparisons between themselves and neighbours, and using statistical analysis to make decisions. This contains the idea of sensing change and differences (both spatial and temporal), rather than making decisions based on the absolute values of the measurements.

A final point that can be made here is that the considerations presented in this report are based entirely on the perceived sensing and measurement requirements. When we begin looking more closely at the communication and decision-making aspects of the system, it may well emerge that these will influence the choice of sensing and measurement techniques. The requirements of the sensing system set out above will not change, but the most effective means of satisfying them is likely to depend on total system considerations.

4.2 Prioritization of Threats and Measurands

In order to set priorities for the development and deployment of sensors and measurement protocols that will allow the useful life of a vehicle to be maximized, it is necessary to make an assessment of the relative importance of the threats the vehicle will face, and of the quantities that must be measured to detect the presence of these threats. This is a complicated task, which has not yet been addressed in any depth by the group.

The factors that govern the relative importance of the threats are the likely consequences of occurrence of the threat and the likelihood, or probability, of its occurrence. These factors are inherently statistical, and are not generally independent: for example, the consequences of a meteoroid impact will depend on its size, mass, relative velocity, location of impact, etc., while the likelihood of an impact may also depend on these factors. Furthermore, the probabilities of occurrence of a number of threats, and in particular the external threats, will depend strongly on the nature and purpose of the vehicle and on the nature of the missions it undertakes. For many of the internal threats, the severity and likelihood of occurrence will depend on the nature of the materials, engines, fuels, etc. used in the vehicle, and thus will change with time and technological development. Therefore, the relative importance of particular threats can only be meaningfully analyzed for a specific set of circumstances.

In practice, the priority for measuring a quantity that will indicate the presence of a threat depends not only on the importance of the threat, but also on the effectiveness of possible responses. There is little point in measuring a quantity if no effective action can be taken as a result. This must be taken into account in deciding which sensors to deploy on a vehicle. On the other hand, in deciding on a development strategy for sensors and measurement systems, it is worth noting that in general the effectiveness of a response will be improved the earlier and more reliably the threat or resulting damage is detected. Good detection reliability depends on both a high probability of detection and a low probability of false indications. Speed and reliability of detection are clearly functions of the sensing system. They can be used, along with the relative importance of the threats, to draw up a target list of sensor and system properties, and to drive sensor and system development.

A further point concerning the prioritization of measurands is that, in most cases, more than one quantity can be used to detect the presence of a threat or the damage it has caused. Equally, some quantities can be used to detect different types of threats. For example, propagating elastic waves (acoustic emission) could, in principle, be used to detect surface impacts, structural failure (cracking, fracture) and some types of material degradation. Therefore, as was noted in the preceding subsection, the types of sensors and the quantities they are used to measure need to be considered from a total system perspective rather than from the point of view of individual threats.

In considering the possible consequences of the threats listed in Section 3, one might be tempted to assign higher priority to those with the potential to produce catastrophic effects on the vehicle. However, the possible responses to a catastrophic event are limited and are rarely entirely satisfactory. It will always be preferable to detect at an early stage the precursors to such events. Therefore, in considering the possible consequences of apparently less significant threats, such as, for example, the various mechanisms for material degradation, it is important to take account of their possible ultimate consequences.

Further consideration will be given to prioritization of threats, measurands and sensors in the final report of this work.

4.3 Roles of the Integrated Sensing System

It was suggested in Section 2 that the integrated sensing system might have distinguishable supervisory and repair/response roles. An example in which these roles may be recognisably different is when a form of damage may be detected and repaired locally, without intervention by a central agent (e.g. by a self-regenerating material supplied with a constant stream of nutrient). As far as the repair function is concerned, there is arguably no need for the damage information to be shared with any other part of the structure. However, it may well be desirable for the supervisory system to be aware of the occurrence of the damage, to determine things like long-term maintenance strategy, supply of nutrients (materials, energy), and to detect possible system malfunction that might be producing higher than normal rates of damage.

4.4 Material Damage vs Sensor or System Malfunction

For some quantities such as material discontinuity or loss of material (e.g. due to fracture or impact damage), the sensing/communication system may itself constitute an effective damage sensor: a lack of information from a localized region could be a useful indicator of damage. However, this raises the issue of whether and how material damage can be distinguished from sensor or system malfunction. One approach to overcoming this is to employ redundancy, not only of signal path as is required for robust communication, but also of sensing modality. For example, if following an impact there is no response from a region of structure, confirmatory evidence of damage might be obtained by optical imaging, by detection of a pressure leak, by changed flight characteristics, etc. We generally follow such a strategy ourselves: when we feel pain, we usually either look or touch the affected area for confirmation. If we detect a lack of sensation (numbness), which is a local failure of the tactile sensory system, we either look at the region or try another sensor, a(nother) finger perhaps.

4.5 Information Loss and Software Reliability Issues

These are major issues that were touched upon briefly in Section 3: they are clearly related. Information loss is the ultimate source of ageing in biological systems. The laws of thermodynamics ensure that it is inevitable, so strategies need to be developed to minimise its effects. There must have been a great deal of work on this problem that can be consulted. The software in an ageless system may take many forms. In biological systems it is contained in, *inter alia*, the chemistry of the constituents of cells and their environments. Software reliability will be limited by information loss, by the complexity of the software, and by the occurrence of circumstances for which it was not designed or adapted (to which it has not yet learnt to respond). The reliability, verification and testing of software is a major topic of current research.

5. Immediate Plans for Further Work

The next major issues to be addressed are the following.

- Simplification of the sensing problem. The aim is to determine a minimum set of sensor types and measurements that can satisfy the diverse requirements of vehicle health monitoring outlined in Section 3.
- Development of concepts for the intelligent NDE system. This is the central issue of the present project, for which the work so far has laid the groundwork.

All of our discussions so far have indicated that the functions of sensing, data processing, information storage, communications and decision-making will be strongly inter-dependent, to the extent that basic concepts for all these areas need to be developed together. One way of making progress would be to have a number of special-interest groups looking at specific areas (research thrusts), with frequent reporting back to each other. However, we have opted for a different and hopefully more effective approach in the first instance.

We plan to have small multi-disciplinary groups consider integrated solutions to highly simplified model problems. Each group will define its own problem, with the only rules being that the structure may be very simple, the material properties must be consistent with the laws of physics, the sensing system should be capable of sensing damage or danger, communicating sensed information, making decisions and responding. The structure should operate in a simple adverse environment that presents threats that require widely differing response times. This is a problem-solving approach to gaining an understanding of the important issues and developing conceptual solutions. We shall see where and how far it leads us.

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The ultimate goal of ageless aerospace vehicles requires the development of materials and structures that are capable of self-assessment and repair. The aim of this project is to develop and examine concepts for intelligent integrated sensing, processing, communication and decision-making systems that could perform the distributed health monitoring functions of a smart vehicle. The purpose of this report is to present a list of the types of threats to which an aerospace vehicle is subject, general strategies for detecting them and/or their consequences, and to identify the quantities that must be measured for implementation of these strategies. Thus, this report establishes in broad terms the requirements that must be satisfied by an integrated vehicle health monitoring system. A number of significant issues are raised and discussed, including the wide range of requirements for the sensing and response system (the quantities that must be measured, and temporal and spatial measurement and response scales), the use of embedded and movable sensors, the need to distinguish structural damage from sensor or system failure, issues of information loss and sensor and system reliability, and the need to adopt an integrated approach to the solution of sensing, processing, communication and decision-making design problems. Whatever the capabilities of future materials for self-repair or regeneration, it is concluded that there will be a need for an integrated vehicle health monitoring system.</td></tr>
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